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Slip-Model-Compatible and Bio-Inspired Robotic Leg with Reconfigurable Length

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Abstract: We present a novel robotic leg design with reconfigurable length. The design combines key features from bio-mechanical principles into a novel robotic leg with only two actuated degrees of freedom (DOF). The leg configuration with one rotary hip joint and one prismatic knee joint makes it compatible to the Spring Loaded Inverted Pendulum (SLIP) model and will therefore potentially allow direct transfer of suitable control parameters obtained by the simulation of the SLIP model [3]. We have implemented the first prototype and conducted preliminary hopping experiments based on energy-efficient hopping at optimal frequency in human experiment [1]. We measured the ground reaction force and electrical power consumption of the module over a range of hopping frequencies. Our results suggest that the leg driven at its optimal frequency is more dynamic and energy efficient. The externally measured ground reaction forces are very consistent with the results obtained in [1].

Keywords: Legged robots, energy efficiency, spring-mass model.

1. INTRODUCTION

Legged robot locomotion has been progressing over recent years supported by the fact that legged robots have the potential to traverse more efficiently rough terrain than the wheeled robots [2]. Inspiration for these designs mainly comes from nature as animal running, hopping and jumping yet present the most efficient and astonishing solution towards energy-efficient legged locomotion. The mechanics of legged animals are composed of many complex components. Some of the core properties of these mechanics can be captured by a simple spring-mass model (SLIP) [3], which makes this model is a promising solution towards building and controlling better legged robots.

Pioneering work has been demonstrated by Marc Raibert in his single legged planar hopper [2]. It uses two actuated DOFs, one rotary to control the forward and the backward motion and a second pneumatically powered telescopic leg for restoring energy and ground interaction. The SCOUT II quadruped robot is able to locomote in fast and dynamic gaits, with only one active rotary DOF and passive linear compliance [4]. Nevertheless, the use of one DOF limits its performance on rough terrain. In contrast, the Tekken robot utilizes three active DOFs per leg and is potentially capable to handle rough terrain up to certain extent [5]. However, with the accumulated motors weights, dynamically fast gaits are difficult to achieve.

In this paper, we present a novel robotic leg design with reconfigurable length using two actuated DOFs, which combines the strengths of the SCOUT II and Tekken robot, namely the lower DOF and the high motion flexibility. The design is based on a number of specifications, some of which are derived from bio-mechanical studies: light-weight, compact, high-speed and back-drivable vertical DOF with the ability to inject and regulate the required energy into the system, linear compliance that allows easy force measurement needed for impedance control, large range of joint motion, and variable-height ground clearance.

In the next section, we describe the design and implementation details of the leg prototype. We have performed some preliminary experiments with a single leg setup and report on our measurement results based on the electrical power consumption and ground reaction forces at varying hopping frequencies.

2. DESIGN AND IMPLEMENTATION

Based on the specifications listed above, we have designed and implemented the first leg prototype. As shown in Fig.1, The physical prototype uses two actuated DOFs, one rotary (the hip) to oscillate the leg within the range of 180^0 and a second (the knee) which is defined as a prismatic joint to alter and adjust the module length within the range of 100 mm. Both joints can be directly operated from the trunk segment. Thus, the weight of the leg segment can be considerably reduced.

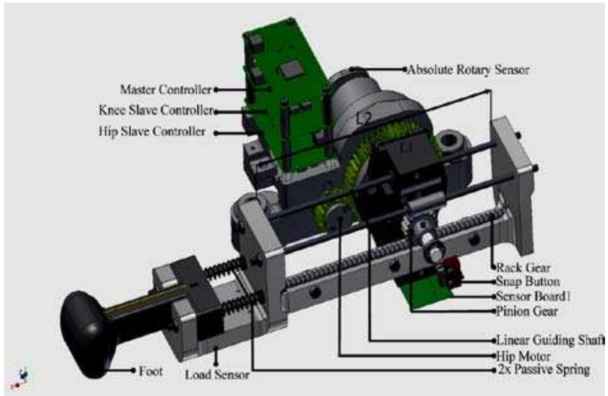

Fig. 1 Leg prototype; overall dimension (LxWxH: 80x123x240mm); weight: 0.75Kg; K per spring: 0.98 N/mm}; Translational speed (knee): 136.4 mm/s.

The prismatic knee motion is implemented by using a pinion and rack gear mechanism. We have also inserted two compression springs to introduce linear compliance in series with the leg segment. The combination of the prismatic knee joint and linear compliance provide the following capabilities: (i) The leg can inject and regulate the amount of energy needed for effective and efficient ground interaction during locomotion, (ii) It allows variable-height ground clearance, (iii) When integrated in a multi-legged robot, it provides the possibility for the robot to adapt its morphological parameters (leg length and center of mass), according to the current environment or task, (iv) The linear spring allows energy storage through passive compliance and provides easy force measurement for impedance control, which can add active compliance to the system.

In addition to these capabilities, the leg configuration with one rotary hip joint and one prismatic knee joint makes it compatible to the Spring Loaded Inverted Pendulum (SLIP) model. This would allow direct transfer of suitable control parameters obtained by the SLIP model and significantly reduces the search space of optimal control parameters in the future. The current leg design is modular. Thus, the complete Quadruped robot can be realized by combining four such modules together with the trunk module.

3. EXPERIMENTAL RESULTS

The performance of the leg was tested in a sagittal plane against the gravity on a force plate. The hopping gait was selected to systematically perform experiment based on the measurements of optimal frequency in [1]. During the experiment, the straight posture of the module was maintained by actuating the hip motor at a constant angle and in-place hopping was carried out by operating the knee motor at different control frequencies. At each frequency, the total power consumption and the vertical ground reaction force (GRF) were measured.

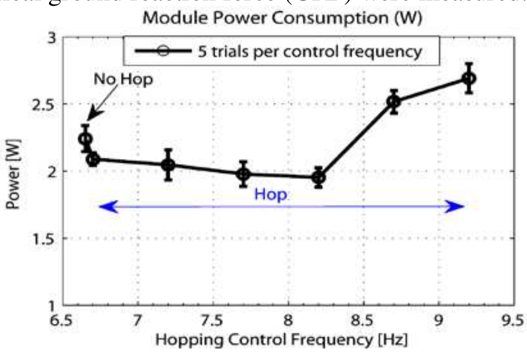

Fig. 2 Determining the optimal frequency by investigating the effect of different frequencies on the module power consumption while hopping.

Fig.2 shows the power consumption at different control frequencies (averaged over 5 trials per frequency). At 6.65 Hz, no hopping was observed and the average electrical power consumption of the module was about 2.242 ±0.096 W. When the control frequency was increased to 6.7 Hz, the module started to hop and the amount of power consumption dropped. When we increased the frequency further, the consumption decreased further until it reached a minimum at 8.2 Hz. At higher frequencies, the electrical power consumption increased again significantly. Thus, we concluded that 8.2 Hz is the optimal frequency of the leg module.

Fig. 3 (a) shows the vertical force exerted on the ground by the system during the ground contact phase, measured using a force plate, which is consistent with results obtained in human hopping in (b). According to [1], the time window, when the reaction force exceeded one body weight during landing and take-off is equivalent to half of the resonant period, i.e., T/2.

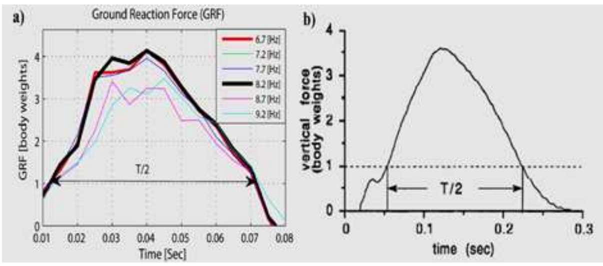

Fig. 3 (a) GRF measured in hopping of the leg prototype, each line is the mean GRF of five successive hops per control frequency; b) GRF measured in human hopping, taken from [1]

We obtained this time window by using the data shown in Fig.3 (a) 59.6 ±0.001 ms. Hence, the optimal frequency was $f\_res = 1/T$ = 8.39 ±0.087 Hz. Further, the effective stiffness of our robotic leg was computed by using the equation $k= m\omega^2$ = 2084.74 ±43.31 N/m, where m=0.75 kg is the mass of the module. Fig.4 shows a sequence of the hopping at the optimal frequency. About 20 mm ground clearance was observed.

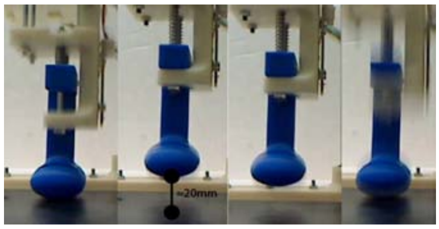

Fig. 4 Hopping frame sequence, starting from mid-stance touch-down to take-off and from take-off to landing.

4. CONCLUSION

We present a novel biologically inspired two-DOF leg with reconfigurable length, which is compatible to the SLIP model. We evaluated the preliminary performance of the leg module on the hopping gait based on the concept of energy-efficient hoping at optimal frequency [1]. We plan to further develop and investigate the dynamical properties and performance of the presented leg design in walking and running, and to validate the results in comparison to simulations based on the SLIP model.

5. ACKNOWLEDGMENT

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